

A Four-leaf Clover-shaped Coding Metasurface For Ultra-wideband Diffusion-like Scattering

YASIR Saifullah YANG Guomin* XU Feng

(Key Laboratory for Information Science of Electromagnetic Waves,
Fudan University, Shanghai 200433, China)

Abstract: In this paper, a novel four-leaf clover-shaped coding metasurface is proposed and applied to achieve an ultra-wideband diffusion-like scattering. The proposed metasurface element has rotational symmetry; hence, it produces similar reflection characteristics for both x - and y -polarized waves. To realize a 1-bit coding metasurface, two elements are chosen that have a phase difference of $180^\circ \pm 37^\circ$ from 15.5 to 40.5 GHz. An optimization algorithm is applied to get the best arrangement of unit cells in the array to attain the wideband RCS reduction. The four-leaf clover-shaped metasurface can attain more than 10 dB RCS reduction from 15.5 to 26.5 GHz and 30.5 to 40.5 GHz. A prototype of the proposed design is fabricated, and an experiment is carried out to validate the performance of the metasurface. The proposed concept of four-leaf clover-shaped coding metasurface is an effective solution for wideband RCS reduction applications.

Key words: Coding metasurface; Water cycle algorithm; Radar Cross-Section (RCS); Diffusion-like scattering; Four-leaf clover

DOI: [10.12000/JR21061](https://doi.org/10.12000/JR21061)

Reference format: YASIR Saifullah, YANG Guomin, and XU Feng. A four-leaf clover-shaped coding metasurface for ultra-wideband diffusion-like scattering[J]. *Journal of Radars*, 2021, 10(3): 382–390. DOI: 10.12000/JR21061.

引用格式: YASIR Saifullah, 杨国敏, 徐丰. 四叶草形超宽带漫散射编码超表面[J]. 雷达学报, 2021, 10(3): 382–390. DOI: 10.12000/JR21061.

四叶草形超宽带漫散射编码超表面

YASIR Saifullah 杨国敏* 徐丰

(复旦大学电磁波信息科学教育部重点实验室 上海 200433)

摘要: 该文提出了一种结构新颖的四叶草形编码超表面, 并利用该超表面实现了超宽带漫散射。所提出的编码超表面具有旋转对称性, 它对 x 极化和 y 极化波产生相似的反射特性。为了实现1比特编码超表面, 该文设计了在15.5~40.5 GHz的频率范围内且相位差为 $180^\circ \pm 37^\circ$ 的两个超表面单元。采用优化算法得到阵列中单元的最佳排列, 从而实现了宽带RCS的缩减。四叶草形编码超表面可以在15.5~26.5 GHz和30.5~40.5 GHz这两个频带内实现10 dB的RCS缩减。该文加工了该编码超表面并与仿真结果进行了比较, 从而有效验证了所设计的四叶草形编码超表面可以在宽频带内实现RCS的缩减。

关键词: 编码超表面; 水循环算法; 雷达散射截面; 漫散射; 四叶草形

中图分类号: TN61

文献标识码: A

文章编号: 2095-283X(2021)03-0382-09

1 Introduction

Metasurfaces have attracted attention in re-

cent years due to their unique characteristic to manipulate wavefronts. Metasurfaces can realize the fascinating applications that are non-existent in natural materials by introducing abrupt changes in phase, amplitude, and polarization of the incident ElectroMagnetic (EM) at sub-wavelength.

The metasurfaces are more advantageous than the 3D metamaterials for various applica-

Manuscript received May 11, 2021; Revised June 21, 2021; Published online June 24, 2021.

*Communication Author: YANG Guomin

E-mail: guominyang@fudan.edu.cn

Foundation Item: The National Key Research and Development Program of China (2017YFA0100203)

Corresponding Editor: FENG Yijun

tions because of their less thickness, easy fabrication, and low complexity. In the last decade, metasurfaces have been applied to realize many fascinating applications including beam manipulation^[1], subwavelength focusing^[2] electromagnetic cloak^[3], holography^[4], and perfect absorber^[5]. The concept of coding and programmable metasurface is introduced recently, which characterizes meta-atom as a digital bit with a value of “0” or “1”. In the case of coding metasurface, “0” and “1” represent two types of elements with a reflection phase of 0° and 180° , respectively^[6]. By arranging the two kinds of elements in the two-dimensional plane, a digital metasurface is realized to control the electromagnetic waves.

Several designs of the Artificial Magnetic Conductor (AMC) have been presented in the literature for RCS reduction application^[7]. A chessboard-like configuration of AMC and Perfect Electric Conductor (PEC) is used to realize RCS reduction by using the principle of opposite phase cancellation to minimize the specular reflection^[8]. The major limitation chessboard-like configuration of PEC and AMC is the bandwidth limitation of AMC. Outside the operating frequency of AMC, it behaves as a PEC and the phase cancellation condition is not satisfied anymore. To overcome this limitation, two AMC structures are designed which resonate at different frequencies^[9]. Such kind of chessboard-like configuration based on two kinds of AMC structures can be used to realize wideband RCS reduction. A wideband polarization rotation reflective surface based on the AMC is presented that can achieve a Polarization Conversion Ratio (PCR) of 96% and the proposed design is applied to realize wideband RCS reduction^[10].

In the last decade, coding metasurfaces have attracted significant attention, and have been applied to realize numerous applications including beam manipulation, diffusion-like scattering, and absorption. A chaos-based metasurface is presented to achieve the wideband RCS reduction based on the relation of the phase distribution of coding metasurface and spatiotemporal chaos patterns^[11]. A broadband RCS reduction is demon-

strated by careful arrangements of unit cells to produce the diffusion-like scattering which distributes the scattering energy in many directions and minimizes the specular reflection of incident EM waves^[12].

Since there could be countless arrangements based on the random combinations of digital elements, there is a requirement to find the optimal configuration of unit cells. Genetic algorithm^[13–15] and Particle Swarm optimization^[16–18] have been used in literature to optimize array factors to get the optimum arrangement of unit cells for better diffusion-like-scattering. A Particle Swarm Optimization (PSO) algorithm is applied to the array factor to find the optimum arrangements of unit cells^[19]. A fast design method is proposed for wideband metasurface design by using a non-linear fitting method instead of the Pancharatnam-Berry (PB) phase, and the genetic algorithm is applied for array optimization^[20].

In this paper, we proposed a novel four-leaf clover-shaped coding metasurface and applied it to realize an ultra-wideband diffusion-like scattering. By optimization the dimension of leaf, two elements are designed which have a phase difference of $180^\circ \pm 37^\circ$ from 15.5 to 40.5 GHz. An optimization algorithm is applied to get the best arrangement of unit cells to achieve the wideband diffusion-like scattering. The simulation and experimental results agree well and hence the proposed design can be used for wideband RCS reduction applications.

2 Design of Metasurface Unit Cell

The schematic model of the four-leaf clover-shaped coding metasurface unit cell is shown in Fig. 1. The unit element is a sandwich structure with the four-leaf clover-shaped metallic pattern as a resonator, the middle dielectric material as a spacer, and the bottom metallic layer as ground. The size of the unit cell is $5 \times 5 \times 1.5 \text{ mm}^3$ and the four-leaf clover-shaped resonator having a thickness of 0.035 mm is printed on F4B substrate with relative permittivity of 2.65 and a loss tangent of 0.001. The unit cell can be used for polarization-insensitive application as it produces the same response for x - and y -polarizations because

of the rotational symmetry of the unit cell. Two different sizes of four-leaf clovers are designed to represent the two digital states of a 1-bit coding metasurface. By changing the size of four-leaf clovers, the phase response of metasurface unit cells changes. To achieve the phase difference of $180^\circ \pm 37^\circ$ between the two types of unit cells, the dimensions of the four-leaf clover are optimized.

For full-wave simulations, CST Microwave Studio with frequency-domain solver is used to simulate the proposed unit cell. The periodic boundary conditions are applied along the x - and y -axis whereas the Floquet port is employed along the z -axis. The simulation results for phase and magnitude responses are shown in Fig. 2 (a) and Fig. 2(b), respectively. The simulated phase response shows that a phase difference of 180° is

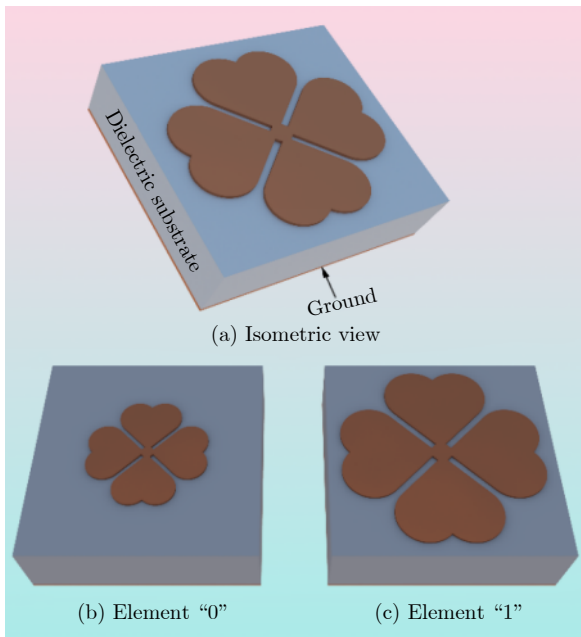
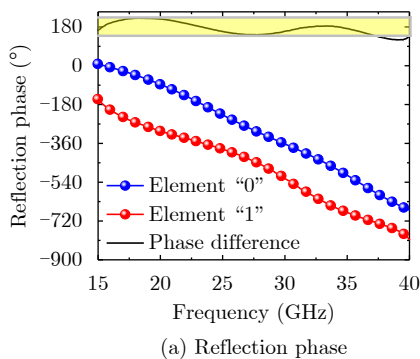


Fig. 1 The schematic of proposed unit cell



(a) Reflection phase

achieved from 15.5 to 40.5 GHz, while the value of simulated magnitude is around -0.2 dB.

3 Optimized Array Design for Diffusion-like Scattering

Once the four-leaf clover-shaped metasurface unit element is designed, the two digital elements are arranged on a two-dimensional plane to realize the metasurface to control electromagnetic waves. To realize the diffusion-like scattering, the element “0” and element “1” can be arranged in a random wave. There could be countless random arrangements of digital elements, hence, we applied an optimization algorithm to find the optimized arrangement of unit cells for better diffusion-like scattering.

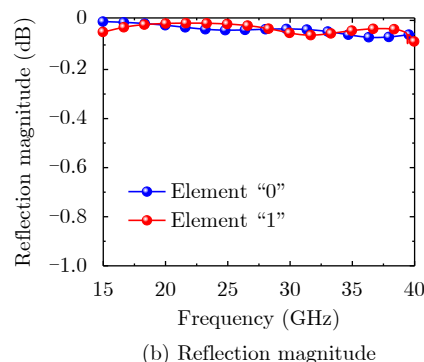
If the P and Q are the numbers of elements along the x - and y -axis, respectively, then the scattering pattern for the $P \times Q$ array is given by

$$E(\theta, \varphi) = EP(\theta, \varphi) \cdot AF(\theta, \varphi) \quad (1)$$

where EP is the element pattern, θ is the elevation angle, φ is the azimuth angle. The array factor AF can be expressed as

$$AF(\theta, \varphi) = \sum_{p=1}^P \sum_{q=1}^Q \exp \left\{ jkd \left[\left(p - \frac{1}{2} \right) \cdot u + \left(q - \frac{1}{2} \right) \cdot v \right] + j\Phi(p, q) \right\} \quad (2)$$

where $u = \sin\theta\cos\varphi$, $v = \sin\theta\sin\varphi$, the size of the unit cell is d , P and Q are the number of unit cells along the x - and y -axis. The phase of coding metasurface element $j\Phi(m, n)$ is the most important factor. For a 1-bit coding metasurface, the phase of the individual coding element could be 0° or 180° . The array is designed by careful placement of element “0” and element “1” to realize a



(b) Reflection magnitude

Fig. 2 Simulation results of reflection phase and magnitude

better diffusion-like scattering. The Water Cycle Algorithm (WCA) is used to obtain the optimum arrangement of element “0” and element “1”. The water cycle algorithm offers better solutions than other optimizers in terms of efficiency and the number of function evaluations^[21]. The flow chart of the water cycle algorithm is presented in Fig. 3.

To achieve the optimum diffusion-like scattering, the fitness function is given by

$$\text{fitness} = \min(\text{AF}_{\max}) \quad (3)$$

The 2D and 3D scattering pattern of the

four-leaf clover-shaped coding metasurface is demonstrated in Fig. 4 (a) and Fig. 4(b), respectively. The water algorithm is applied for 100 iterations with a population size of 100. The convergence characteristics of the algorithm are presented in Fig. 5. For the minimum array factor, the corresponding arrangement of element “0” and element “1” are shown in the coding matrix in Fig. 6. The final array is designed based on the optimized coding matrix to achieve optimum RCS reduction. An array of 40×40 unit cells with a su-

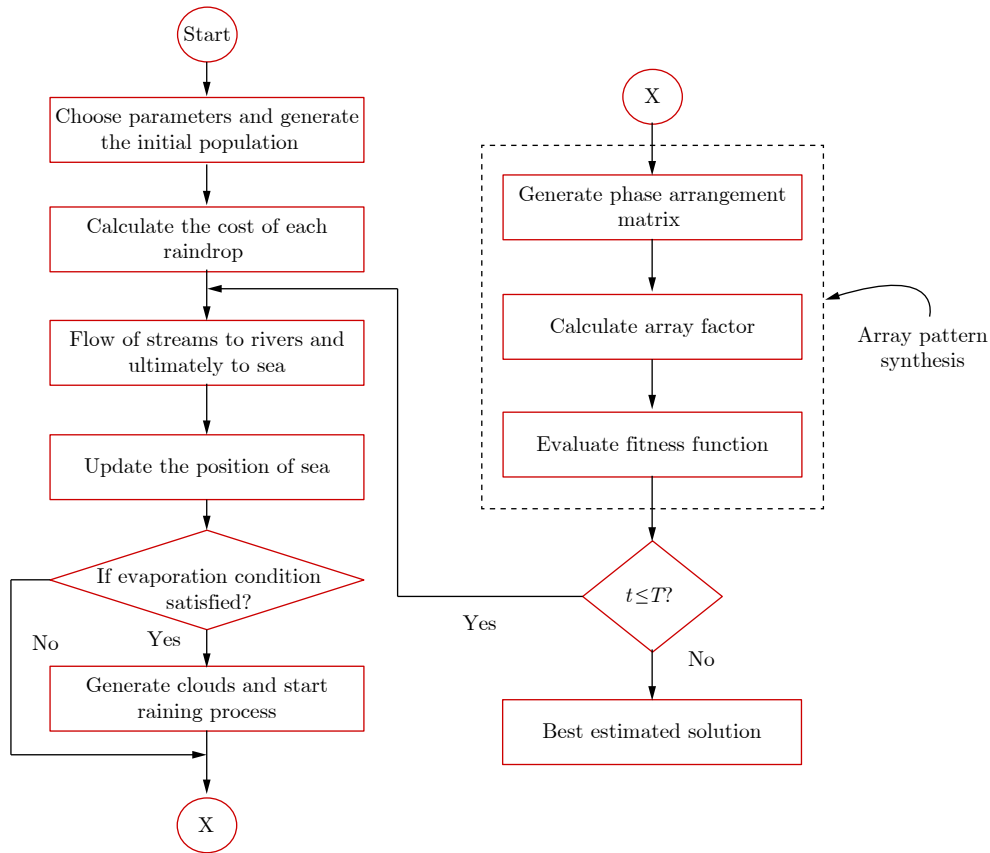
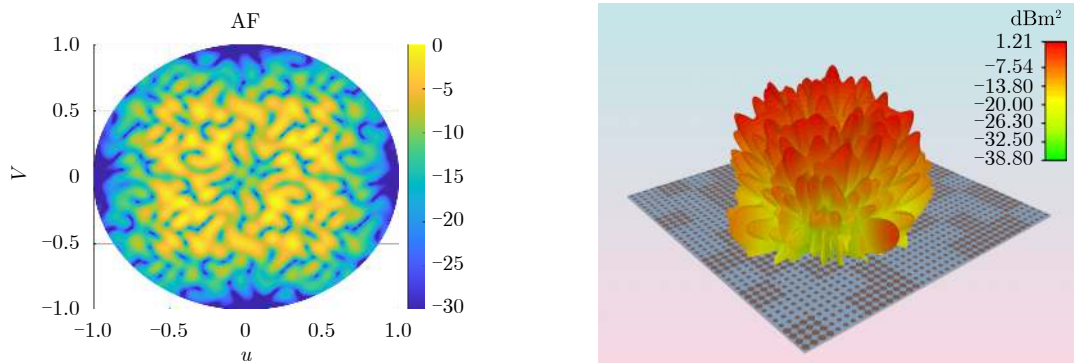


Fig. 3 Flow chart of water cycle algorithm



(a) The results of optimized scattering obtained from MATLAB

(b) The simulation results of the four-leaf clover-based coding metasurface

Fig. 4 Simulation results of the four-leaf clover-based coding metasurface

per-cell size of 4×4 is designed, whereas the coding matrix is 10×10 .

The array simulations were performed using CST Microwave Studio and simulation results are shown in Fig. 7. The far-field simulation results of the proposed 1-bit optimized coding metasurface and PEC at 16.5 GHz, 23.5 GHz, and 39.5 GHz, and the results are shown in Fig. 7. The proposed metasurface has the RCS of 1.21 dBsm, 3.41 dBsm, and 7.26 dBsm at 16.5 GHz, 23.5 GHz, and 39.5 GHz, respectively. An optimized arrangement of the metasurface unit cells is used to realize the diffusion-like scattering. The reflected wave from the metasurface is dispersed in several directions and hence, the specular reflection is reduced. At 16.5 GHz, 23.5 GHz, and 39.5 GHz, the RCS reduction of 16.8 dBsm, 17.6 dBsm, and 18 dBsm is achieved as compared to the same size of PEC.

To verify the concept efficiency proposed metasurface, the RCS of the proposed design is compared with PEC from 15.5 to 40.5 GHz and the results are shown in Fig. 8. An ultra-wide-band RCS reduction of 10 dB is attained from

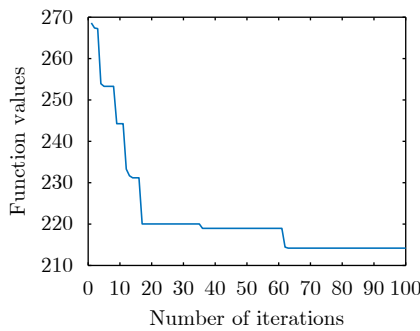


Fig. 5 Convergence characteristics of proposed WCA algorithm

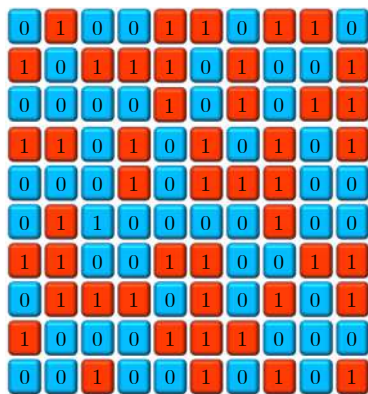


Fig. 6 Optimized arrangement of element '0' and element '1' obtained from MATLAB to form the coding matrix

15.5 to 26.5 GHz and 30.5 to 40.5 GHz under normal incidence as compared with a copper sheet of the same size.

4 Results and Discussions

The Printed Circuit Board (PCB) technology is used to fabricate the prototype of four-leaf clover-shaped coding metasurface and the sample is as presented in Fig. 9.

To analyze the performance of the proposed metasurface, the measurement of the fabricated sample was carried out in the anechoic chamber and the measurement setup is demonstrated in Fig. 10. The experimental setup consists of a vector network analyzer (Agilent N5227A), horn antennas, and a fabricated prototype of the proposed metasurface. Three sets of Ku-, K-, and Ka-

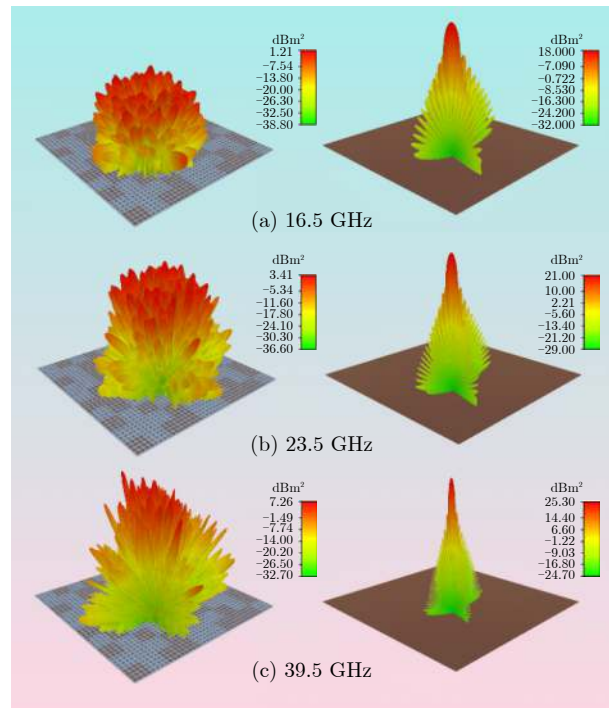


Fig. 7 The 3D scattering patterns of the four-leaf clover-shaped coding metasurface (left column) and the PEC (right column)

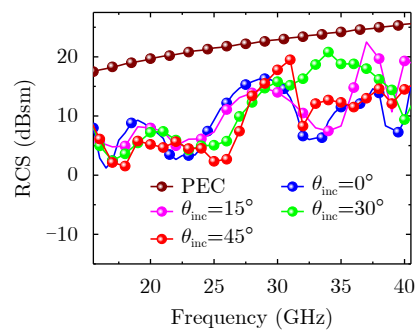


Fig. 8 The RCS of proposed coding metasurface and PEC

band horn antennas are used for measurement to cover the bandwidth from 15.5 to 40.5 GHz. The sample is placed in the far-field of the antenna and far-field condition is given by

$$R > \frac{2D^2}{\lambda_{\min}} \quad (4)$$

To verify the performance, the measured RCS of the proposed metasurface is compared with the simulated RCS of metasurface and PEC as depicted in Fig. 11. The RCS reduction of 10 dB is achieved for normal incidence from 15.5

to 26.5 GHz and 30.5 to 40.5 GHz, whereas more than 6 dB RCS reduction is observed from 26.5 to 30.5 GHz.

However, the small difference between the simulation and measurement results is mainly caused by fabrication error and measurement tolerance. To highlight the advantages of the proposed research, a comparison of this study is drawn with literature and presented in Tab. 1.

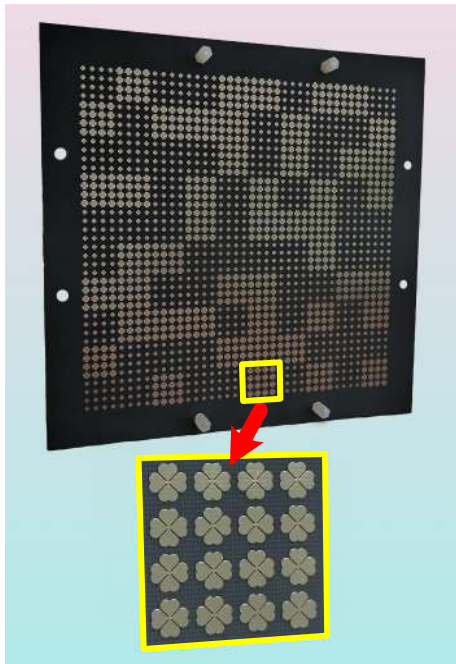


Fig. 9 The fabricated sample of four-leaf clover-shaped coding metasurface

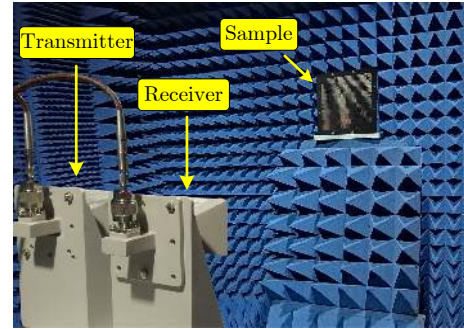


Fig. 10 Experimental setup in an anechoic chamber

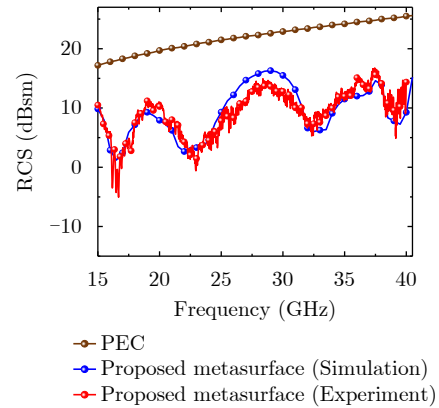


Fig. 11 Comparison of simulation and measurement results

Tab. 1 Comparison of our work with earlier works

Ref.	Freq. band (GHz)	σ_R (dB)	Metasurface arrangement	Thickness	FBW (%)
[22]	11.60~18.65	10	Random	$0.15\lambda_0$	46
[23]	9.9~19.8	10	Random	$0.15\lambda_0$	66
[24]	8~18	10	Random	$0.13\lambda_0$	77
[25]	7.2~15.6	10	Random	$0.12\lambda_0$	73
[26]	12.2~23.4	10	Spiral coding	$0.12\lambda_0$	62
[27]	5.57~7.37	10	Ergodic	$0.06\lambda_0$	28
[28]	5.8~12.2	10	GA	$0.14\lambda_0$	77
[29]	6.94~9.23	10	GA	$0.05\lambda_0$	28
[20]	12~24	10	GA	$0.12\lambda_0$	66
[30]	8~15	10	Random	$0.10\lambda_0$	0.47
This work	15.5~26.5, 30.5~40.5	10	WCA	$0.13\lambda_0$	80

λ_0 is the free-space wavelength corresponding to the center frequency of the operation bandwidth.

FBW: The fractional bandwidth $FBW = (f_H - f_L) / f_c$, $f_c = (f_H + f_L) / 2$

σ_R : RCS reduction

The proposed four-leaf clover-shaped coding metasurface has Fractional BandWidth (FBW) of 80% with a thickness of $0.13\lambda_0$ that makes the proposed design wideband with less thickness. As compared with binary optimization algorithm which can only be applied for 1-bit metasurface, here, we have introduced DWCA which can be extended towards multi-bit metasurface designs.

5 Conclusion

A novel four-leaf clover-shaped coding metasurface is designed and applied to achieve an ultra-wideband diffusion-like scattering. By optimization the dimension of the four-leaf clover, two elements are selected with a phase difference of $180^\circ \pm 37^\circ$ from 15.5 to 40.5 GHz. An optimization algorithm is applied to get the best arrangement of unit cells to attain the ultra-wideband RCS reduction. More than 10 dB RCS reduction is obtained from 15.5 to 26.5 GHz and 30.5 to 40.5 GHz as compared with a copper sheet of the same size. Furthermore, the RCS reduction of more than 6 dB is realized from 26.5 to 30.5 GHz. The proposed design is verified through simulation and experiment. Therefore, the proposed concept of four-leaf clover-shaped coding metasurface is an effective solution for wideband RCS reduction applications.

References

- [1] MA Qian, BAI Guodong, JING Hongbo, *et al.* Smart metasurface with self-adaptively reprogrammable functions[J]. *Light: Science & Applications*, 2019, 8: 98. doi: [10.1038/s41377-019-0205-3](https://doi.org/10.1038/s41377-019-0205-3).
- [2] ARBABI A, HORIE Y, BAGHERI M, *et al.* Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission[J]. *Nature Nanotechnology*, 2015, 10(11): 937–943. doi: [10.1038/mnano.2015.186](https://doi.org/10.1038/mnano.2015.186).
- [3] SCHURIG D, MOCK J J, JUSTICE B, *et al.* Metamaterial electromagnetic cloak at microwave frequencies[J]. *Science*, 2006, 314(5801): 977–980. doi: [10.1126/science.1133628](https://doi.org/10.1126/science.1133628).
- [4] ZHENG Guoxing, MÜHLENBERND H, KENNEY M, *et al.* Metasurface holograms reaching 80% efficiency[J]. *Nature Nanotechnology*, 2015, 10(4): 308–312. doi: [10.1038/mnano.2015.2](https://doi.org/10.1038/mnano.2015.2).
- [5] LI Yong and ASSOUAR B M. Acoustic metasurface-based perfect absorber with deep subwavelength thickness[J]. *Applied Physics Letters*, 2016, 108(6): 063502. doi: [10.1063/1.4941338](https://doi.org/10.1063/1.4941338).
- [6] CUI Tiejun, QI Mengqing, WAN Xiang, *et al.* Coding metamaterials, digital metamaterials and programmable metamaterials[J]. *Light: Science & Applications*, 2014, 3(10): e218. doi: [10.1038/lsa.2014.99](https://doi.org/10.1038/lsa.2014.99).
- [7] ZHENG Yuejun, GAO Jun, CAO Xiangyu, *et al.* Wideband RCS reduction of a microstrip antenna using artificial magnetic conductor structures[J]. *IEEE Antennas and Wireless Propagation Letters*, 2015, 14: 1582–1585. doi: [10.1109/LAWP.2015.2413456](https://doi.org/10.1109/LAWP.2015.2413456).
- [8] PAQUAY M, IRIARTE J C, EDERRA I, *et al.* Thin AMC structure for radar cross-section reduction[J]. *IEEE Transactions on Antennas and Propagation*, 2007, 55(12): 3630–3638. doi: [10.1109/TAP.2007.910306](https://doi.org/10.1109/TAP.2007.910306).
- [9] GALARREGUI J C I, PEREDA A T, DE FALCÓN J L M, *et al.* Broadband radar cross-section reduction using amc technology[J]. *IEEE Transactions on Antennas and Propagation*, 2013, 61(12): 6136–6143. doi: [10.1109/TAP.2013.2282915](https://doi.org/10.1109/TAP.2013.2282915).
- [10] JIA Yongtao, LIU Ying, GUO Y J, *et al.* Broadband polarization rotation reflective surfaces and their applications to RCS reduction[J]. *IEEE Transactions on Antennas and Propagation*, 2016, 64(1): 179–188. doi: [10.1109/TAP.2015.2502981](https://doi.org/10.1109/TAP.2015.2502981).
- [11] WANG He, HUANG Jiyao, WANG Honglin, *et al.* Chaos-based coding metasurface for radar cross-section reduction[J]. *Journal of Physics D: Applied Physics*, 2019, 52(40): 405304. doi: [10.1088/1361-6463/ab2dc6](https://doi.org/10.1088/1361-6463/ab2dc6).
- [12] CHEN Jie, CHENG Qiang, ZHAO Jie, *et al.* Reduction of radar cross section based on a metasurface[J]. *Progress in Electromagnetics Research*, 2014, 146: 71–76. doi: [10.2528/PIER14022606](https://doi.org/10.2528/PIER14022606).
- [13] SUI Sai, MA Hua, WANG Jiafu, *et al.* Absorptive coding metasurface for further radar cross section reduction[J]. *Journal of Physics D: Applied Physics*, 2018, 51(6): 065603. doi: [10.1088/1361-6463/aaa3be](https://doi.org/10.1088/1361-6463/aaa3be).
- [14] LI Sijia, CAO Xiangyu, XU Liming, *et al.* Ultra-broadband

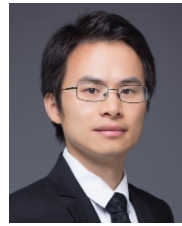
- reflective metamaterial with rcs reduction based on polarization convertor, information entropy theory and genetic optimization algorithm[J]. *Scientific Reports*, 2016, 6: 37409. doi: [10.1038/srep37409](https://doi.org/10.1038/srep37409).
- [15] LI Haipeng, WANG Guangming, CAI Tong, *et al.* Wideband transparent beam-forming metadvice with amplitude- and phase-controlled metasurface[J]. *Physical Review Applied*, 2019, 11(1): 014043. doi: [10.1103/PhysRevApplied.11.014043](https://doi.org/10.1103/PhysRevApplied.11.014043).
- [16] SUN Hengyi, GU Changqing, CHEN Xinlei, *et al.* Broadband and broad-angle polarization-independent metasurface for radar cross section reduction[J]. *Scientific Reports*, 2017, 7: 40782. doi: [10.1038/srep40782](https://doi.org/10.1038/srep40782).
- [17] SU Jianxun, LU Yao, LIU Jiayi, *et al.* A novel checkerboard metasurface based on optimized multielement phase cancellation for superwideband RCS reduction[J]. *IEEE Transactions on Antennas and Propagation*, 2018, 66(12): 7091–7099. doi: [10.1109/TAP.2018.2870372](https://doi.org/10.1109/TAP.2018.2870372).
- [18] YANG Jianing, HUANG Cheng, SONG Jiakun, *et al.* Ultra-broadband low scattering metasurface utilizing mixed-elements based on phase cancellation[J]. *Journal of Physics D: Applied Physics*, 2020, 53(2): 025102. doi: [10.1088/1361-6463/ab4b2e](https://doi.org/10.1088/1361-6463/ab4b2e).
- [19] HAJI-AHMADI M J, NAYYERI V, SOLEIMANI M, *et al.* Pixelated checkerboard metasurface for ultra-wideband radar cross section reduction[J]. *Scientific Reports*, 2017, 7(1): 11437. doi: [10.1038/s41598-017-11714-y](https://doi.org/10.1038/s41598-017-11714-y).
- [20] SUI Sai, MA Hua, LV Yueguang, *et al.* Fast optimization method of designing a wideband metasurface without using the Pancharatnam–Berry phase[J]. *Optics Express*, 2018, 26(2): 1443–1451. doi: [10.1364/OE.26.001443](https://doi.org/10.1364/OE.26.001443).
- [21] ESKANDAR H, SADOLLAH A, BAHREININEJAD A, *et al.* Water cycle algorithm—a novel metaheuristic optimization method for solving constrained engineering optimization problems[J]. *Computers & Structures*, 2012, 110/111: 151–166. doi: [10.1016/j.compstruc.2012.07.010](https://doi.org/10.1016/j.compstruc.2012.07.010).
- [22] FENG Maochang, LI Yongfeng, ZHENG Qiqi, *et al.* Two-dimensional coding phase gradient metasurface for rcs reduction[J]. *Journal of Physics D: Applied Physics*, 2018, 51(37): 375103. doi: [10.1088/1361-6463/aad5ad](https://doi.org/10.1088/1361-6463/aad5ad).
- [23] ZHENG Qiqi, LI Yongfeng, ZHANG Jieqiu, *et al.* Wideband, wide-angle coding phase gradient metasurfaces based on pancharatnam-berry phase[J]. *Scientific Reports*, 2017, 7: 43543. doi: [10.1038/srep43543](https://doi.org/10.1038/srep43543).
- [24] SU Pei, ZHAO Yongjiu, JIA Shengli, *et al.* An ultra-wideband and polarization-independent metasurface for RCS reduction[J]. *Scientific Reports*, 2016, 6: 20387. doi: [10.1038/srep20387](https://doi.org/10.1038/srep20387).
- [25] ZHUANG Yaqiang, WANG Guangming, LIANG Jiangang, *et al.* Random combinatorial gradient metasurface for broadband, wide-angle and polarization-independent diffusion scattering[J]. *Scientific Reports*, 2017, 7(1): 16560. doi: [10.1038/s41598-017-16910-4](https://doi.org/10.1038/s41598-017-16910-4).
- [26] YUAN Fang, WANG Guangming, XU Hexiu, *et al.* Broadband RCS reduction based on spiral-coded metasurface[J]. *IEEE Antennas and Wireless Propagation Letters*, 2017, 16: 3188–3191. doi: [10.1109/LAWP.2017.2768129](https://doi.org/10.1109/LAWP.2017.2768129).
- [27] LIU Xiao, GAO Jun, XU Liming, *et al.* A coding diffuse metasurface for RCS reduction[J]. *IEEE Antennas and Wireless Propagation Letters*, 2016, 16: 724–727. doi: [10.1109/LAWP.2016.2601108](https://doi.org/10.1109/LAWP.2016.2601108).
- [28] SU Jianxun, HE Huan, LI Zengrui, *et al.* Uneven-layered coding metamaterial tile for ultra-wideband RCS reduction and diffuse scattering[J]. *Scientific Reports*, 2018, 8(1): 8182. doi: [10.1038/s41598-018-26386-5](https://doi.org/10.1038/s41598-018-26386-5).
- [29] HAN Xinmin, XU Haojun, CHANG Yipeng, *et al.* Multiple diffuse coding metasurface of independent polarization for RCS reduction[J]. *IEEE Access*, 2020, 8: 162313–162321. doi: [10.1109/ACCESS.2020.3021650](https://doi.org/10.1109/ACCESS.2020.3021650).
- [30] CHEN Ke, CUI Li, FENG Yijun, *et al.* Coding metasurface for broadband microwave scattering reduction with optical transparency[J]. *Optics Express*, 2017, 25(5): 5571–5579. doi: [10.1364/OE.25.005571](https://doi.org/10.1364/OE.25.005571).



YASIR Saifullah (1989–) is currently pursuing his Ph.D. degree with the School of Information Science and Technology, Fudan University. His research interests include microwave, metamaterial, coding, dielectric and programmable metasurfaces.



YANG Guomin (1979–) received the B.S. degree (Hons.) in communication engineering from the Xi'an University of Technology, Xi'an, China, in 2002, the M.S. degree in electronic engineering from Shanghai Jiao Tong University, Shanghai, China, in 2006, and the Ph.D. degree in electrical and computer engineering from Northeastern University, Boston, MA, USA, in 2010. In 2010, he joined the Faculty of the School of Information and Technology, Fudan University, Shanghai, China, where he is currently Professor. He has authored 58 journal publications and 58 conference papers. His research interests include antenna miniaturization, magnetodielectric materials, intelligent metamaterials, frequency-selective surfaces, microwave wireless power transfer, RF energy harvesting, and inverse scattering problems in electromagnetics.



XU Feng (1982–) received the B.E. degree (Hons.) in information engineering from Southeast University, Nanjing, China, in 2003, and the Ph.D. degree (Hons.) in electronic engineering from Fudan University, Shanghai, China, in 2008. From 2008 to 2010, he was a Post-Doctoral Fellow with the National Oceanic and Atmospheric Administration (NOAA) Center for Satellite Applications and Research, Camp Springs, MD, USA. From 2010 to 2013, he worked with Intelligent Automation Inc., Rockville, MD, USA, and NASA Goddard Space Flight Center, Greenbelt, MD, USA, as a Research Scientist. In 2012, he was selected for China's Global Experts Recruitment Program and subsequently returned to Fudan University, in 2013, where he is a Professor. His research interests include electromagnetic scattering modeling, SAR information retrieval, and radar system development. Dr. Xu was a recipient of the second-class National Nature Science Award of China in 2011, the 2014 Early Career Award of the IEEE Geoscience and Remote Sensing Society, and the 2007 SUMMA Graduate Fellowship in the advanced electromagnetics area.